CP Violation in B Decays in the LHC Era

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- Basic Framework
- Brief Look @ Current Picture
- Perspectives for B Physics @ LHC: $\longrightarrow$ Entering a New Territory
- Targets for an e^+e^- "Super-Flavour Factory"
- Concluding Remarks

Basic Framework

Quark Flavour Physics & CP Violation

$\longrightarrow$ key players in the history of the Standard Model (SM):

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_{\rm L} \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

flavour physics has since continued to progress ...

Status of the Standard Model

- Quark flavour physics and CP violation:

  Yukawa sector of EW SSB ($\rightarrow$ quark masses) $\Rightarrow$ rich phenomenology:

  – The *interplay between theory & experiments* at the e^+e^- B factories (BaBar & Belle) resulted in many new insights into these topics.
  – With the exception of a few "flavour puzzles" (not yet conclusive because of large errors), the SM flavour sector is in good shape.
  – But still a large territory of the flavour-physics landscape is unexplored:

  $\rightarrow$ target of the LHCb experiment

- We have indications that the SM *cannot* be complete:

  – Neutrino masses $\neq 0$: suggest see-saw mechanism, GUT scenarios ...
  – Baryon asymmetry of the Universe (SM cannot generate it ...)
  – The long-standing problem of dark matter ...

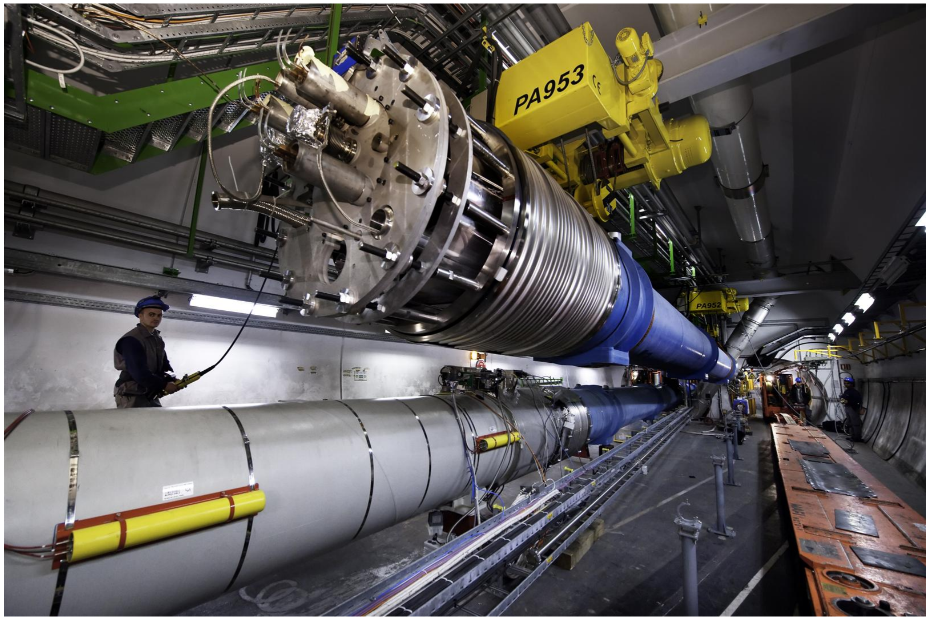
  $\oplus$ fundamental theoretical questions (hierarchy problem, ...)

Status of the LHC

- Start-up phase of the LHC is currently in progress: [$\longrightarrow$ talk by S. Bethke]
  - First beam on September 10th, 2008.
  - Incident in LHC sector 3-4 on September 19th $\longrightarrow$ repair needed!
  - LHC scheduled to restart in 09/2009, providing *first physics data* ...

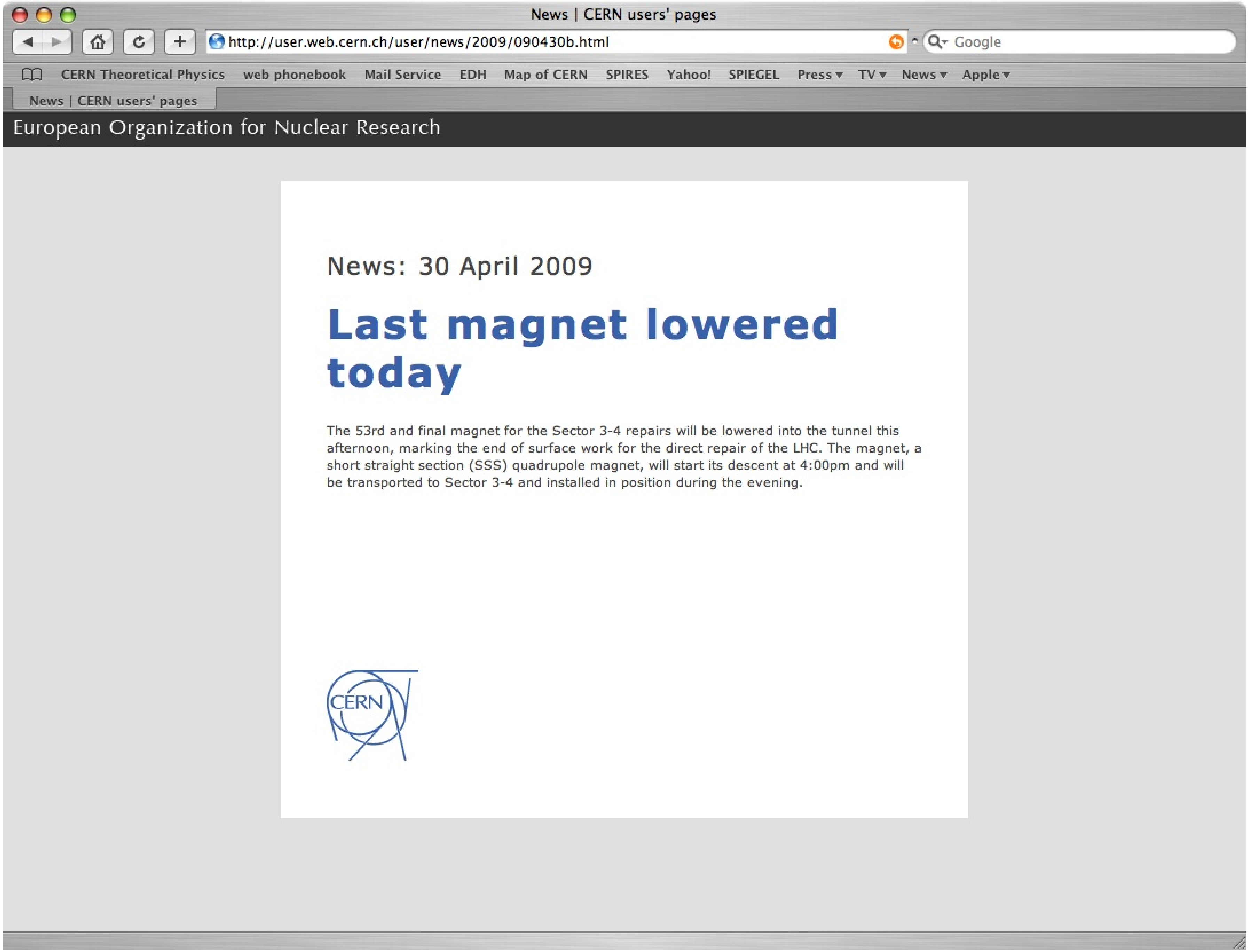
    [Further info: `http://public.web.cern.ch/public/`]

- Transport of a magnet from LHC sector 3-4 to the surface to be repaired:



(December 2008)

- Most recent news:



In Pursuit of New Physics with Flavour Probes

- Goal: detect effects of $\mathcal{L}_{\rm NP}$ in weak processes

  $\longrightarrow$ requires obviously a solid understanding of the $\mathcal{L}_{\rm SM}$ "background"!

- Challenging hierarchy of scales:

$$\underbrace{\Lambda_{\rm NP} \sim 10^{(0\ldots?)}\,\text{TeV} \gg \Lambda_{\rm EW} \sim 10^{-1}\,\text{TeV}}_{\text{(very) short distances}} \ggg \underbrace{\Lambda_{\rm QCD} \sim 10^{-4}\,\text{TeV}}_{\text{long distances}}$$

- Powerful theoretical concepts/techniques: "Effective Field Theories"
  - Heavy degrees of freedom (NP particles, top, Z, W) are "integrated out" from appearing explicitly: $\longrightarrow$ *short-distance loop functions.*
  - Calculation of *perturbative QCD corrections*.
  - *Renormalization group* allows the summation of large $\log(\mu_{\rm SD}/\mu_{\rm LD})$.

- Applied to the SM and various NP scenarios, such as the following:
  - MSSM, UED, WED, LH, LHT, Z' models, 4th generation, ...

[See the corresponding talks @ this workshop]

- The *key problem:* strong interactions $\longrightarrow$ "hadronic" uncertainties

  - The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. B, D and K mesons.

  - In the formalism sketched above, the long-distance physics is separated from the short-distance part ["operator product expansion" (OPE)]:

    $\Rightarrow$ process-dependent, *non-perturbative "hadronic" parameters!?*
    [$\longrightarrow$ lattice QCD: lots of progress (e.g., B_K), but still a long way to go ...]

- The B-meson system is a *particularly promising* flavour probe:

  - Simplifications through the large b-quark mass $m_b \sim 5\,\text{GeV} \gg \Lambda_{\text{QCD}}$.

  - Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.

  - Tests of *clean SM relations* that could be spoiled by NP ...

- These features led to the "rise of the B mesons": $\longrightarrow$ our focus

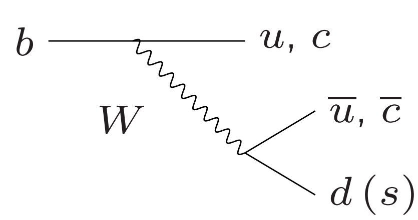
  ... after $K \to \pi\pi$ decays[1] have dominated for 35 years!

[1] $K \to \pi\nu\bar{\nu}$ with SM BRs=$\mathcal{O}(10^{-11})$ very clean, but exp. very challenging [$\longrightarrow$ Gorbahn's talk].

Key Processes for the Exploration of CP Violation

→ non-leptonic $B \to f$ decays (only quarks in the final states):

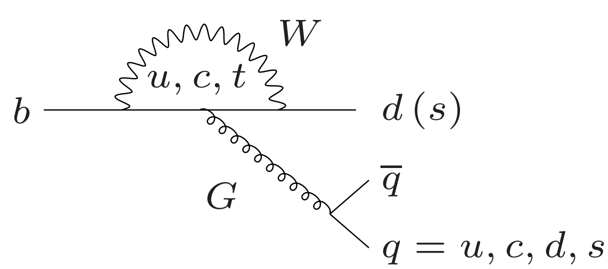
- Tree diagrams:

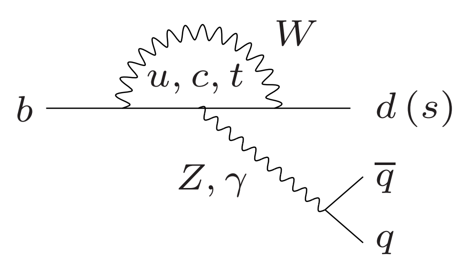


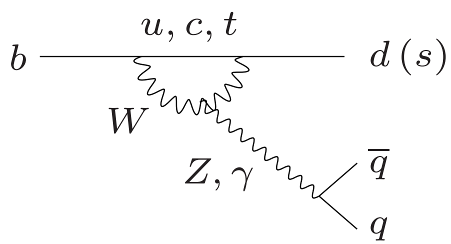
- "Penguin" diagrams: → loop processes:

  ◇ QCD penguins:

  ◇ Electroweak (EW) penguins:







Amplitude Structure in the Standard Model

- CKM unitarity and CP conservation of strong interactions: $\Rightarrow$

$$
\begin{aligned}
A(\overline{B} \to \overline{f}) &= e^{+i\varphi_1}|A_1|e^{i\delta_1} + e^{+i\varphi_2}|A_2|e^{i\delta_2} \\
A(B \to f) &= e^{i[\phi_{\mathrm{CP}}(B) - \phi_{\mathrm{CP}}(f)]}\left[e^{-i\varphi_1}|A_1|e^{i\delta_1} + e^{-i\varphi_2}|A_2|e^{i\delta_2}\right]
\end{aligned}
$$

  – CP-violating weak phases $\varphi_{1,2}$ originate from CKM factors $V_{jr}^{*}V_{jb}$.

  – CP-conserving "strong" amplitudes $|A_{1,2}|e^{i\delta_{1,2}}$ involve the hadronic matrix elements of four-quark operators:

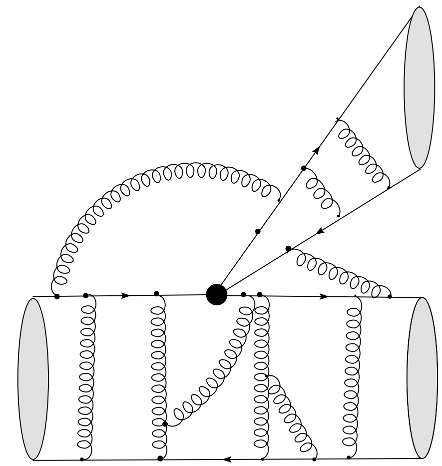
$$
|A_j|e^{i\delta_j} = \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}_{\text{"unknown"}}
$$

$\Rightarrow$ encode the *hadron dynamics* of the considered decay!

  – The *convention-dependent* phase factor $e^{i[\phi_{\mathrm{CP}}(B) - \phi_{\mathrm{CP}}(f)]}$ has to *cancel* in all physical observables, in particular in the CP asymmetries!

Developments in the Last ~ 10 Years ...

$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$



- QCD factorization (QCDF): [→ talks by Bell & Bartsch]

  Beneke, Buchalla, Neubert & Sachrajda (1999–2001); ...

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

Data ⇒ *theoretical challenge remains ...*

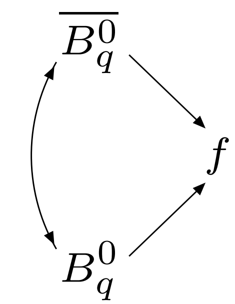
[Buras *et al.*; Ali *et al.*; Ciuchini *et al.*; Chiang *et al.*; ...]

Circumvent the Calculation of the $\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle$:

- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\to$ typically strategies to determine the UT angle γ):
  - *Exact* relations: class of pure "tree" decays (e.g. $B \to DK$).
  - *Approximate* relations, which follow from the *flavour symmetries* of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_{\mathrm{F}}$:

$$B \to \pi\pi,\ B \to \pi K,\ B_{(s)} \to KK.$$

- Decays of neutral B_d or B_s mesons:



Interference effects through B^0_q–$\overline{B^0_q}$ mixing:

  - Lead to "mixing-induced" CP violation $S(f)$, in addition to "direct" CP violation $C(f)$ (caused by interference between decay amplitudes).
  - If one CKM amplitude dominates:

$$\Rightarrow\ \textit{hadronic matrix elements cancel in } S(f), \textit{ while } C(f) = 0$$

  * Example: $B^0_d \to J/\psi\, K_{\mathrm{S}} \quad \Rightarrow \quad S(J/\psi K_{\mathrm{S}}) = \sin 2\beta$

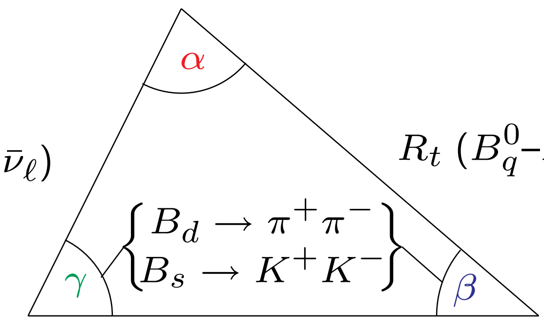
A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$

R_b $(b \to u, c\ell\bar{\nu}_\ell)$

R_t $(B_q^0$–$\bar{B}_q^0$ mixing)



$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ $(B_s \to \psi\phi : \phi_s \approx 0)$

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{matrix} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{matrix}\right\} \text{only trees}$$

$$\left.\begin{matrix} B_d \to D^{(*)\pm}\pi^\mp : \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \gamma + \phi_s \end{matrix}\right\} \text{only trees}$$

- Moreover "rare" decays: $B \to X_s\gamma$, $B_{d,s} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, ...
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

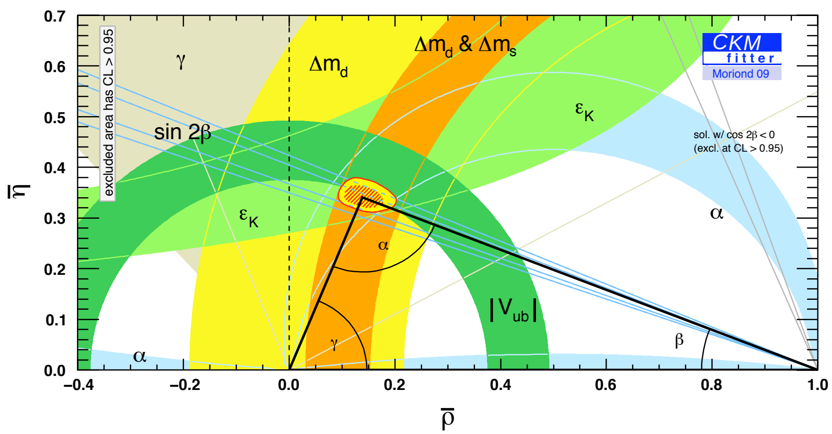
New Physics $\Rightarrow$ Discrepancies

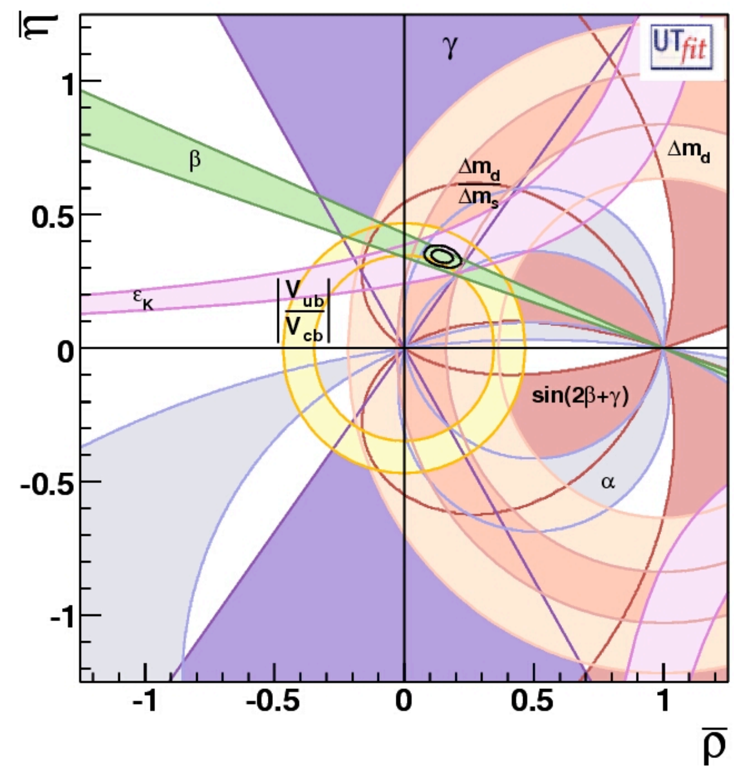
Brief Look @ Current Picture

Status of the Unitarity Triangle

- Two competing groups: $\longrightarrow$ many plots & correlations ...
  - *CKMfitter* Collaboration [http://ckmfitter.in2p3.fr/];
  - *UTfit* Collaboration [http://www.utfit.org]:

$\longrightarrow$ *continuously updated results:*





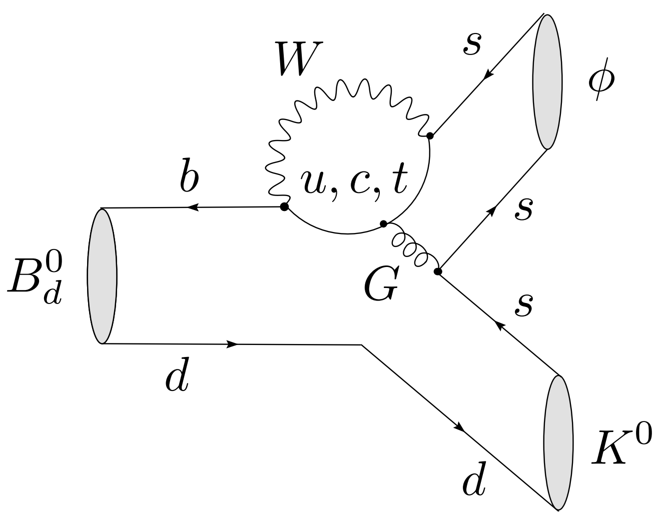
◇ New Physics in Decay Amplitudes:

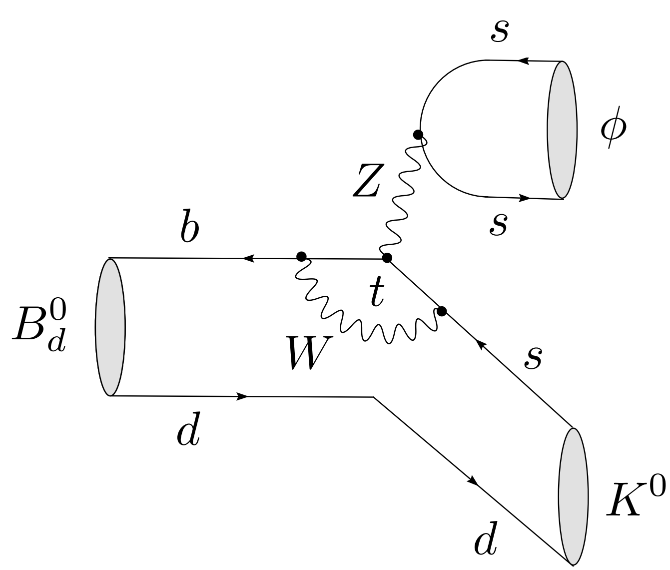
- Typically *small* effects if SM tree processes play the dominant rôle:

  $\rightarrow$ example: $B_d^0 \rightarrow J/\psi K_S$

- Potentially *large* effects in the penguin sector through new particles in the loops or new contributions at the tree level, e.g. SUSY, Z' models:

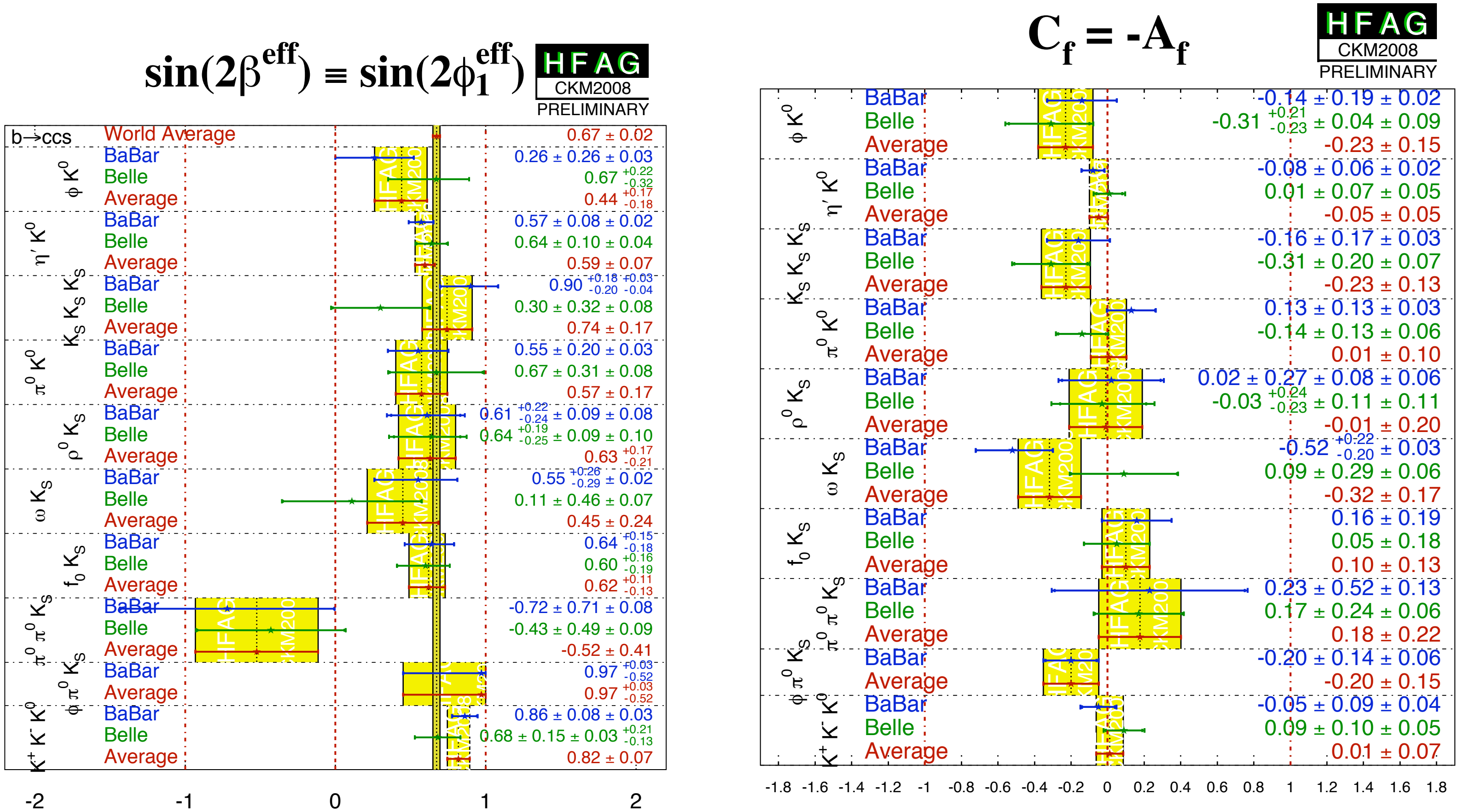
  $\rightarrow$ hot topic: decays that are dominated by $b \rightarrow s$ penguins ...





CP Violation in $b \rightarrow s$ Penguin Modes

- <u>Experimental pattern:</u>



- <u>Moreover:</u> "$B \to \pi K$ puzzle" received quite some attention
  [Buras & R.F. ('00); Beneke & Neubert ('03); Buras, R.F., Recksiegel & Schwab ('03–'06); ...]

$\Rightarrow$ NP could be present, but still cannot be resolved!?

Particularly Interesting Decay: $B^0 \to \pi^0 K^0$

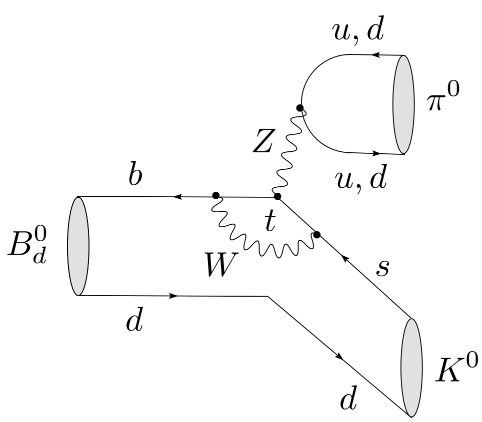
- Time-dependent, CP-violating rate asymmetry:

$$\frac{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) - \Gamma(B^0(t) \to \pi^0 K_S)}{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) + \Gamma(B^0(t) \to \pi^0 K_S)}$$
$$= A_{\pi^0 K_S} \cos(\Delta M_d t) + S_{\pi^0 K_S} \sin(\Delta M_d t)$$

- In the SM, we have – up to doubly Cabibbo-suppressed terms:

$$A_{\pi^0 K_S} \approx 0, \quad S_{\pi^0 K_S} \equiv (\sin 2\beta)_{\pi^0 K_S} \approx \sin 2\beta$$

- EW penguins have a significant impact: $\Rightarrow$ nice for NP to enter!?



$\Rightarrow$ what is the SM picture?

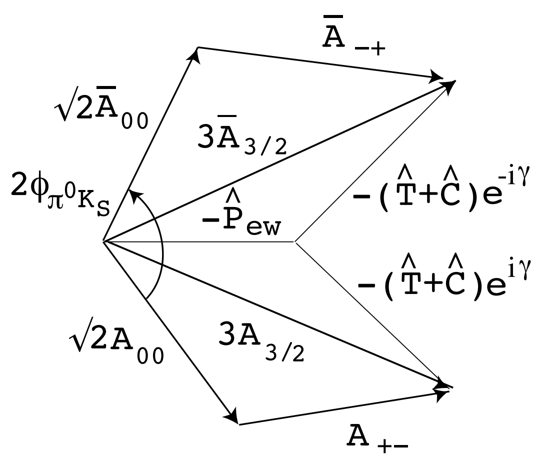
SM Benchmark for the NP Search in $B^0 \to \pi^0 K^0$

- Isospin relation between neutral $B \to \pi K$ amplitudes is the starting point:

$$\sqrt{2}\,A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+) = -\underbrace{\left[(\hat{T}+\hat{C})e^{i\gamma} + \hat{P}_{\rm ew}\right]}_{(\hat{T}+\hat{C})(e^{i\gamma} - q e^{i\omega})} \equiv 3A_{3/2}$$

- $A_{3/2}$ can be fixed through $SU(3)$ for "well-behaved" quantities:
  - $|\hat{T}+\hat{C}| \propto |A(B^+ \to \pi^+\pi^0)|$, i.e. determined from data;
  - $q e^{i\omega} \equiv -\hat{P}_{\rm ew}/(\hat{T}+\hat{C}) \stackrel{\rm SM}{=} 0.66 \times 0.41/R_b$.

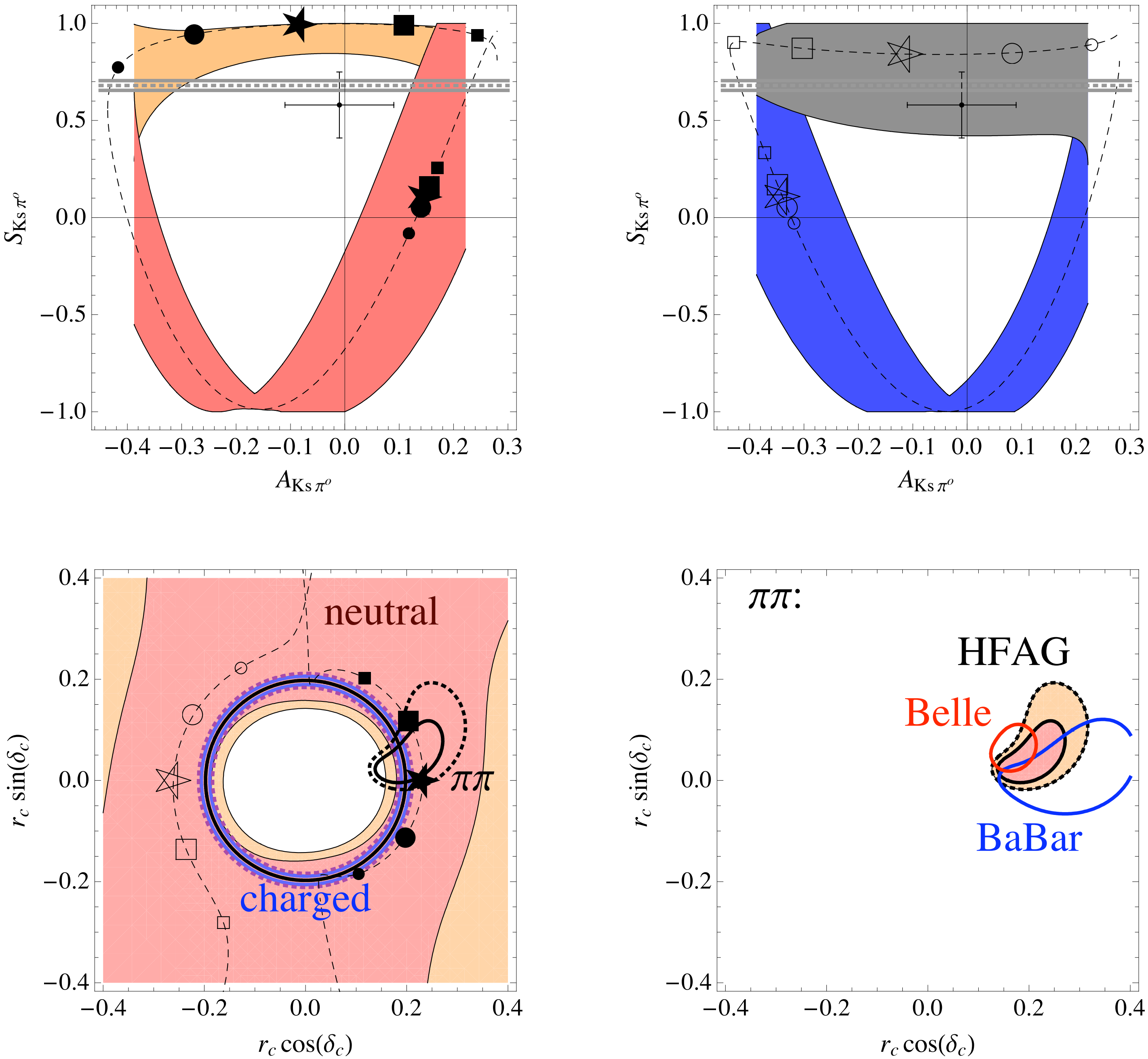
- Triangle construction: $\to$ rates for decays and CP conjugates:



$$S_{\pi^0 K_{\rm S}} = \frac{2|\bar{A}_{00}A_{00}|}{|\bar{A}_{00}|^2 + |A_{00}|^2}\sin(2\beta - 2\phi_{\pi^0 K_{\rm S}})$$

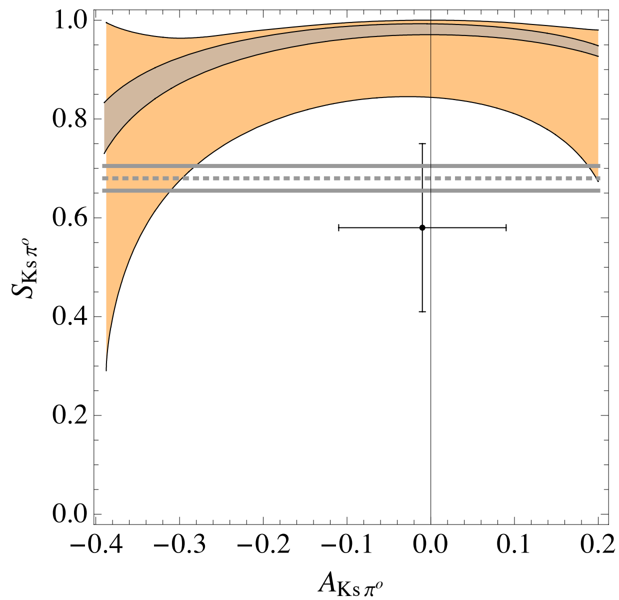
encounter a fourfold ambiguity:
triangles can be flipped around $A_{3/2}$, $\bar{A}_{3/2}$

[R.F., S. Jäger, D. Pirjol and J. Zupan ('08); confirmed by Gronau & Rosner ('08)]



$$r_c e^{i\delta_c} = (\hat{T} + \hat{C})/\hat{P};\ B^+ \to \pi^+ K^0 \to |\hat{P}|$$ ("charged" constraint)

- So we are finally left with the following correlation in observable space:

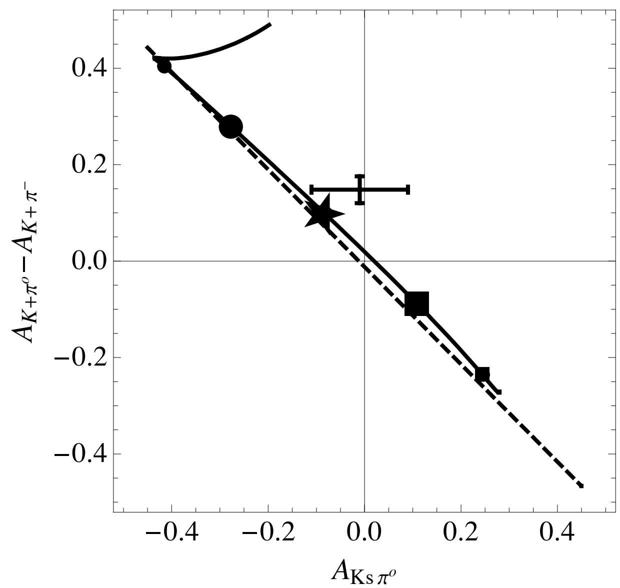


$$S_{\pi^0 K_S} = 0.99^{+0.01}_{-0.08}\Big|_{\text{exp.}}{}^{+0.000}_{-0.001}\Big|_{R_{T+C}}{}^{+0.00}_{-0.11}\Big|_{R_q}{}^{+0.00}_{-0.07}\Big|_{\gamma}$$

- Narrow upper band: $\longrightarrow$ benchmark scenario for future TH uncertainty
  - Relies on an assumed future progress in the calculation of an $SU(3)$-breaking form-factor ratio with 20% uncertainty on the lattice.
  - Sensitivity to modified EW penguins with a new CP-violating phase.
  - Interesting for a future super-B factory...

Direct CP Asymmetries (No B_d^0–$\bar{B}_d^0$ Mixing Involved)

- SM correlation between $A_{\pi^0 K_S}$ and $A_{\pi^0 K^+} - A_{\pi^- K^+}$:



- The difference $A_{\pi^0 K^+} - A_{\pi^- K^+} \neq 0$ has recently received quite some attention as a possible sign of NP [Belle Collaboration, *Nature* **452** (2008) 332].

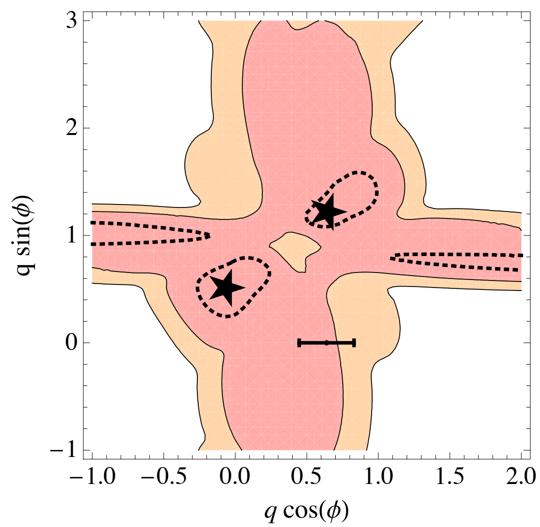
- The data can be accommodated in the SM within the error of $A_{\pi^0 K_S}$, although hadronic amplitudes then deviate from the $1/m_b$ pattern:

$\Rightarrow$ reduce the experimental error of $A_{\pi^0 K_S}$

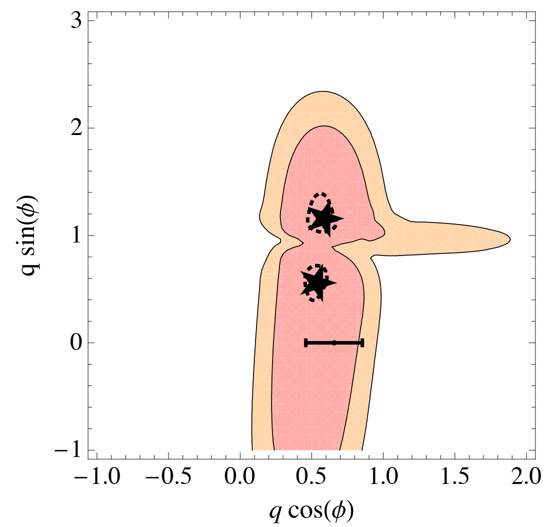
NP Scenario to Resolve the $S_{\pi^0 K_S}$ Discrepancy

- Assume that NP manifests itself as a modified EWP: $q \to q e^{i\phi}$

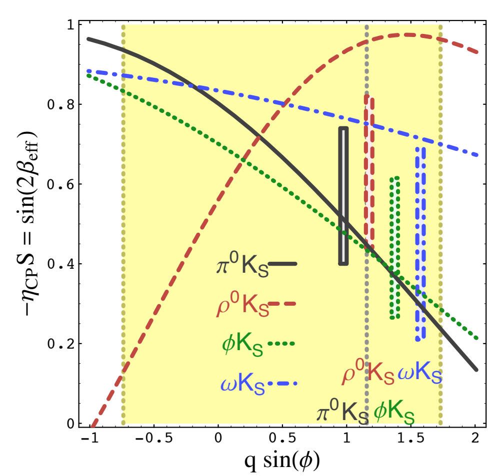
  – χ^2 fits: only $B \to \pi K$:



  – both $B \to \pi K$ and $B \to \pi\pi$:



- Other penguin-dominated $b \to s$ decays can be accommodated as well:

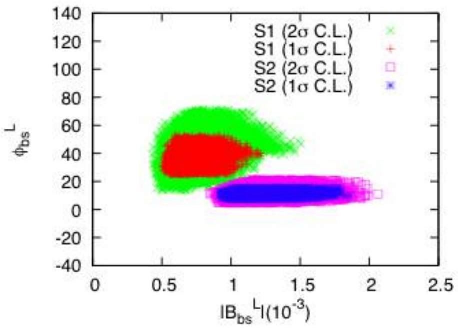


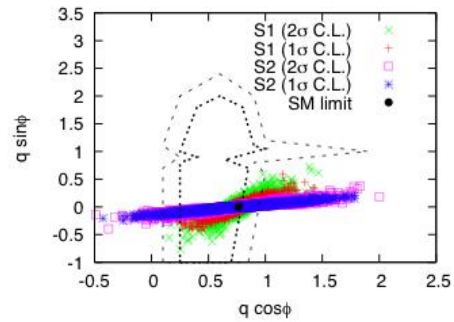
[Illustration in QCDF]

Recent Specific BSM Analysis

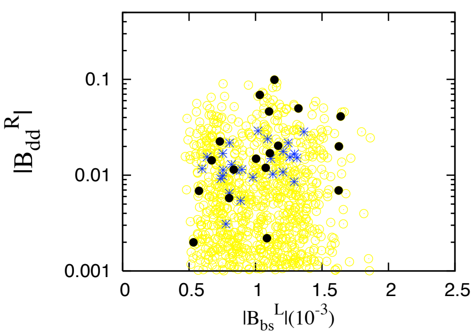
- Models with a family non-universal $U(1)'$:
  - Generation-independent charges for the first two families;
  - small fermion mixing angles.

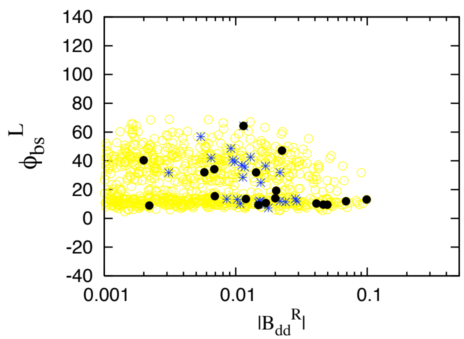
- Constraints from data for B_s^0–$\bar{B}_s^0$ mixing (see below) & $B \to \pi K, \pi\pi$:





- Combination of both constraints (and from CPV in other $b \to s$ modes):



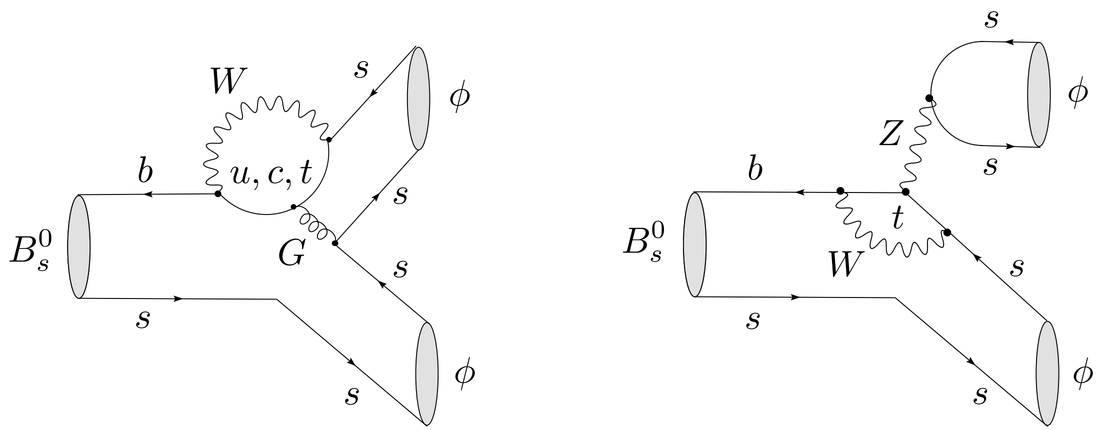


with $M_{Z'} \lesssim (10\text{–}100) M_Z$ approachable at LHC.

[Barger, Everett, Jiang, Langacker, Liu & Wagner ('09); also Chang, Li & Yang ('09)]

LHCb can also address this topic:

- Most promising channel for this experiment: $B_s^0 \to \phi\phi$
  - $\bar{b} \to \bar{s}s\bar{s}$ penguin decay (B_s^0 counterpart of $B_d^0 \to \phi K_S$):

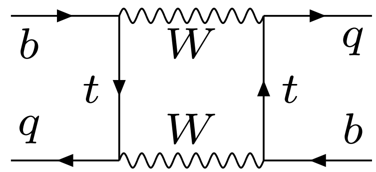


- CP-violating observables of the time-dependent angular distribution of $B_s^0 \to \phi[\to K^+K^-]\phi[\to K^+K^-]$ provide powerful probes for NP!

- Strategy for extracting both NP amplitudes and their strong phases:
  - Use information on CP violation in the $\bar{b} \to \bar{d}s\bar{s}$ decay $B_s^0 \to \phi\bar{K}^{*0}$ to complement the CP-violating observables in $B_s^0 \to \phi\phi$.
  - Flavour-symmetry arguments allow us to control doubly Cabibbo-suppressed (i.e. $\mathcal{O}(\lambda^2)$) SM corrections to the $B_s^0 \to \phi\phi$ observables.

[R.F. & M. Gronau]

◇ New Physics in B_q^0–$\bar{B}_q^0$ mixing:



- NP particles in boxes or tree contributions (e.g. SUSY, Z' models):

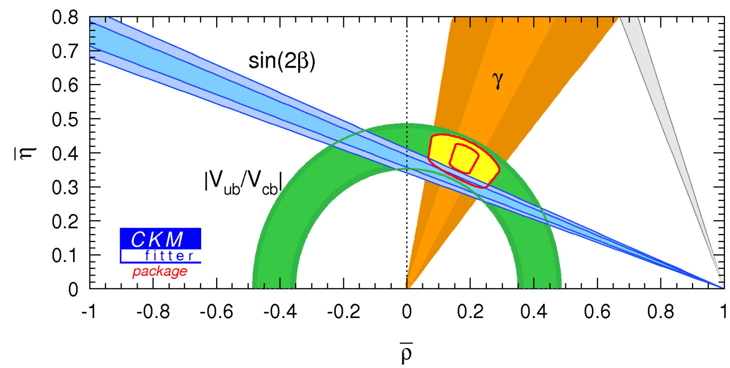
$$\boxed{\kappa_q e^{i\sigma_q} \equiv M_{12}^{q,\mathrm{NP}} / M_{12}^{q,\mathrm{SM}}} \Rightarrow$$

  - Mass difference: $\Delta M_q = \Delta M_q^{\mathrm{SM}} \left|1 + \kappa_q e^{i\sigma_q}\right|$
  - Mixing phase: $\phi_q = \phi_q^{\mathrm{SM}} + \phi_q^{\mathrm{NP}} = \phi_q^{\mathrm{SM}} + \arg(1 + \kappa_q e^{i\sigma_q})$

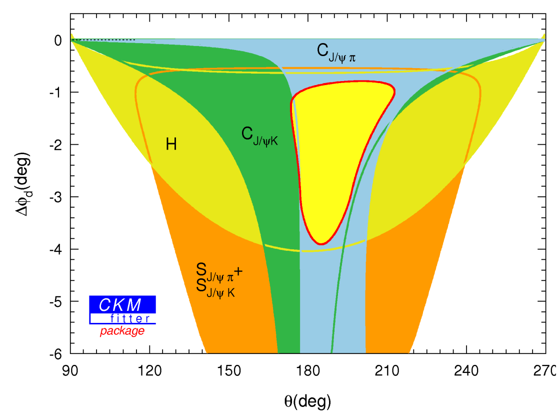
[Details: P. Ball & R.F. (2006)]

Implications of the Data for the B_d^0 System

- Tension in fit of UT: $(\phi_d)_{J/\psi K^0} - 2\beta_{\text{true}} = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ \rightarrow$ NP!?



- SM corrections (penguin effects): $\Rightarrow$ $S(J/\psi K_S) \propto \sin(\phi_d + \Delta\phi_d)$
  - $\Delta\phi_d$ fixed through $B_d^0 \rightarrow J/\psi\pi^0$ data and $SU(3)$ flavour-symmetry:



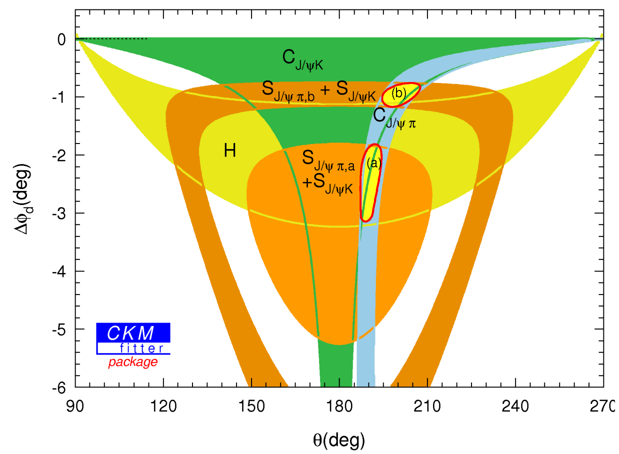
  - Fit to all current data, allowing also for $SU(3)$ breaking:

$\Rightarrow$ $\Delta\phi_d \in [-6.7, 0.0]^\circ \Rightarrow$ softens the tension in the fit of the UT!

[S. Faller, R.F., M. Jung & T. Mannel (2008)]

- NP parameters: $\phi_d^{\rm NP} \in [-14.9, 4.0]^\circ$, i.e. no significant effect.

- Future perspectives (scenarios): $\longrightarrow$ refer to an e^+e^- super-B factory:



  – Since the exp. error of $(\phi_d)_{J/\psi K^0}$ could be reduced to $\sim 0.3^\circ$ (LHCb upgrade and e^+e^- super-B factory), these corrections will be crucial.
  [LHCb: alternative to measure CP violation in $B_s^0 \to J/\psi K_{\rm S}$ (R.F. '99)]

- Interesting observation:

  – The quality of the B-factory data has essentially reached a level of precision where subleading SM effects have to be included!

B Physics at the LHC:

$\longrightarrow$ entering a new territory of the B landscape:

high statistics $\oplus$ *complementarity* to B factories:[2]

fully exploit the B_s-meson system!

[2] e^+e^- B factories operating at the $\Upsilon(4S)$ resonance cannot produce B_s mesons; could go to $\Upsilon(5S)$.

Key Features of the B_s-Meson System

- The B_s^0–$\bar{B}_s^0$ oscillations are *rapid*: $\boxed{\Delta M_s/\Delta M_d \sim 40}$

  $\Rightarrow$ challenging to resolve them experimentally, but actually feasible!

- Expect *sizeable* width difference $\Delta\Gamma_s/\Gamma_s \sim 15\%$ (while $\Delta\Gamma_d/\Gamma_d \sim 0$):

  $\Rightarrow$ $\boxed{\text{interesting for "untagged" studies of } B_s^0, \bar{B}_s^0 \to f\text{:}}$

$$\langle\Gamma(B_s(t) \to f)\rangle \equiv \Gamma(B_s^0(t) \to f) + \Gamma(\bar{B}_s^0(t) \to f) = e^{-\Gamma_{\rm H}^{(s)}t}R_{\rm H} + e^{-\Gamma_{\rm L}^{(s)}t}R_{\rm L}$$

  – The rapidly oscillating $\Delta M_s t$ terms cancel $\Rightarrow$ exp. advantages.

  – Various "untagged" strategies of CP violation were proposed.

  [Dunietz ('95); R.F. & Dunietz ('96); Dunietz, Dighe & R.F. ('99); ...]

- The CP-violating mixing phase is *tiny* in the SM (while $\phi_d \sim 42^\circ$):

  $\boxed{\phi_s^{\rm SM} = -2\lambda^2\eta \approx -2^\circ}$ $\Rightarrow$ great news for probing $\phi_s^{\rm NP} \neq 0^\circ$!

Constraints on NP through ΔM_s

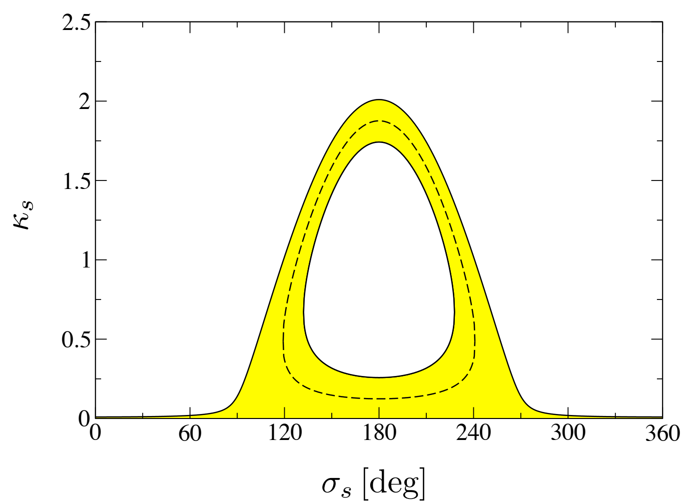
- After long efforts, signals for B_s^0–$\bar{B}_s^0$ mixing at the Tevatron in 2006:

$$\boxed{\Delta M_s = (17.78 \pm 0.12)\,\text{ps}^{-1} \text{ (CDF \& DØ average)}}$$

- SM prediction ($f_{B_s}^2 \hat{B}_{B_s}$ @ lattice): [HPQCD collaboration, hep-lat/0610104]

$$\boxed{\Delta M_s^{\rm SM} = 20.3(3.0)(0.8)\,\text{ps}^{-1}}$$

- Allowed region in the σ_s–κ_s plane: [Update of P. Ball & R.F. (2006)]



$$\Delta M_q = \Delta M_q^{\rm SM} \left|1 + \kappa_q e^{i\sigma_q}\right|$$

$\Rightarrow$ **plenty of space for NP left!**

[also in popular NP scenarios:
SUSY, Z', WED, LHT, 4th gen., ...]

Golden Process to Search for NP in B_s^0–$\bar{B}_s^0$ Mixing:

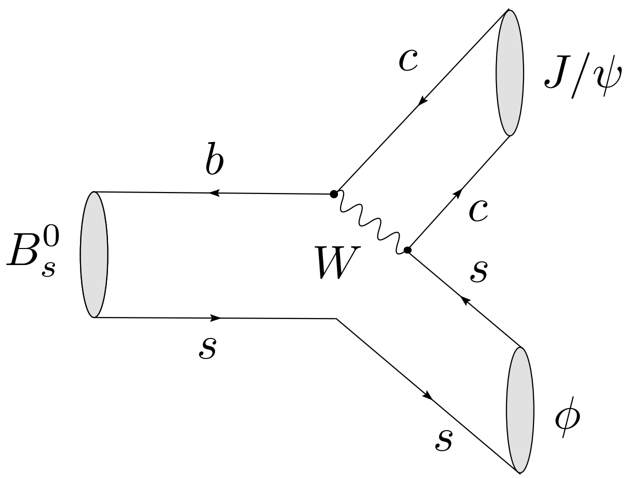
$$\boxed{B_s^0 \to J/\psi\phi}$$

$\longrightarrow$ B_s^0 counterpart of $B_d^0 \to J/\psi K_{\rm S}$ ...

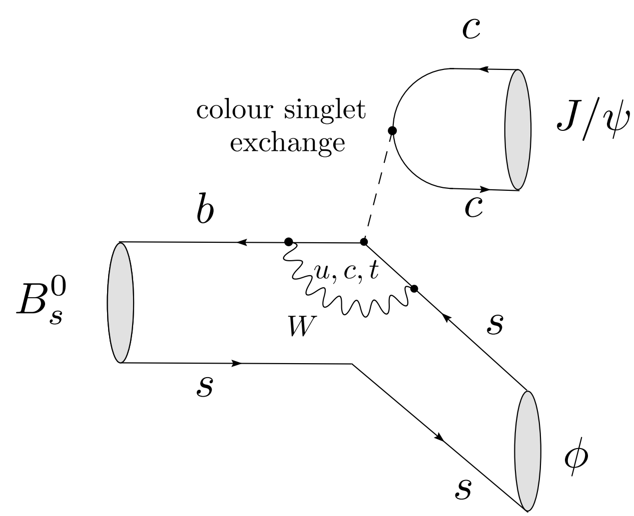
[Dighe, Dunietz & R.F. (1999); Dunietz, R.F. & Nierste (2001)]

Amplitude Structure

- Decay topologies:



$\lambda_c^{(s)} \equiv V_{cs}V_{cb}^*$



$\lambda_j^{(s)} \equiv V_{js}V_{jb}^* \quad (j \in \{u, c, t\})$

- Structure of the decay amplitude:

$$A(B_s^0 \to J/\psi\phi) = \lambda_c^{(s)}(A_{\rm T}^c + A_{\rm P}^c) + \lambda_u^{(s)}A_{\rm P}^u + \lambda_t^{(s)}A_{\rm P}^t$$

- CKM unitarity: $\lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \oplus \epsilon \equiv \lambda^2/(1-\lambda^2) = 0.053 \Rightarrow$

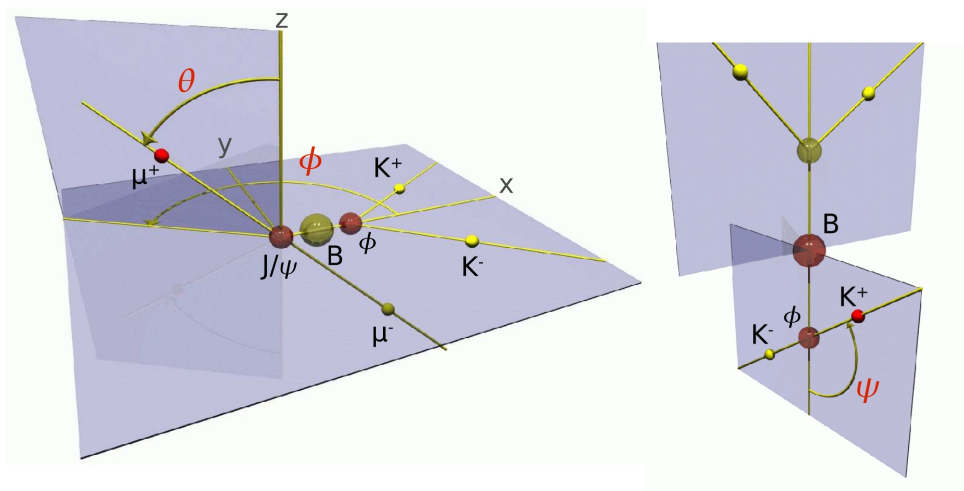
$$A(B_s^0 \to J/\psi\phi) \propto \left[1 + \epsilon a e^{i\vartheta} e^{i\gamma}\right] \qquad a e^{i\vartheta} = R_b \left[\frac{A_{\rm P}^u - A_{\rm P}^t}{A_{\rm T}^c + A_{\rm P}^c - A_{\rm P}^t}\right]$$

Exploring CP Violation with $B_s^0 \to J/\psi\phi$

- There is an important difference with respect to $B_d^0 \to J/\psi K_S$:

  2-vector-meson final state is an admixture of different CP eigenstates.

- Angular distribution of the $J/\psi[\to \mu^+\mu^-]\phi[\to \ K^+K^-]$ decay products:



$$B_s^0 \to J/\psi\phi : \quad f(\Theta,\Phi,\Psi;t) = \sum_k g^{(k)}(\Theta,\Phi,\Psi)b^{(k)}(t)$$

$$\bar{B}_s^0 \to J/\psi\phi : \quad \bar{f}(\Theta,\Phi,\Psi;t) = \sum_k g^{(k)}(\Theta,\Phi,\Psi)\bar{b}^{(k)}(t)$$

$\Rightarrow$ CP eigenstates can be disentangled (rather complicated) ...

Structure of the Observables

- Consider linear pol. states of the vector mesons, which are longitudinal (0) or transverse to their directions of motion. In the latter case, the pol. states may be parallel $(\|)$ or perpendicular $(\perp)$ to one another.

- Linear polarization amplitudes: $A_0(t), \quad A_\|(t), \quad A_\perp(t)$

  - $A_\perp(t)$ describes a CP-odd final-state configuration.
  - $A_0(t)$ and $A_\|(t)$ correspond to CP-even final-state configurations.
  - The observables $b^{(k)}(t)$ are then given as follows:

$$|A_f(t)|^2 \quad (f \in \{0, \|, \perp\})$$

$$\mathrm{Re}\{A_0^*(t)A_\|(t)\}, \quad \mathrm{Im}\{A_f^*(t)A_\perp(t)\} \quad (f \in \{0, \|\}).$$

- CP asymmetries are governed by the following observable $(f \in \{0, \|, \perp\})$:

$$\xi^{(s)}_{(\psi\phi)_f} \propto e^{-i\phi_s}\Big[1 - \underbrace{2\,i\,\lambda^2 a_f e^{i\theta_f}\sin\gamma + \mathcal{O}(\lambda^4)}_{\text{penguin effects}}\Big] \to e^{-i\phi_s}$$

- Two avenues to probe the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s:

$$\boxed{\phi_s = (-2\lambda^2\eta)_{\rm SM} + \phi_s^{\rm NP} \approx -2^\circ + \phi_s^{\rm NP} \approx \phi_s^{\rm NP}}$$

  – *Untagged* observables:

    $\longrightarrow$ do not distinguish between initially present B_s^0 or $\bar{B}_s^0$:

$$\propto \left[(1 \pm \cos\phi_s)e^{-\Gamma_{\rm L}^{(s)}t} + (1 \mp \cos\phi_s)e^{-\Gamma_{\rm H}^{(s)}t}\right]$$

  – *Tagged* data samples:

    $\longrightarrow$ distinguish between initially present B_s^0 or $\bar{B}_s^0$:

$$\longrightarrow \text{ CP asymmetries } \propto \sin(\Delta M_s t)\sin\phi_s$$

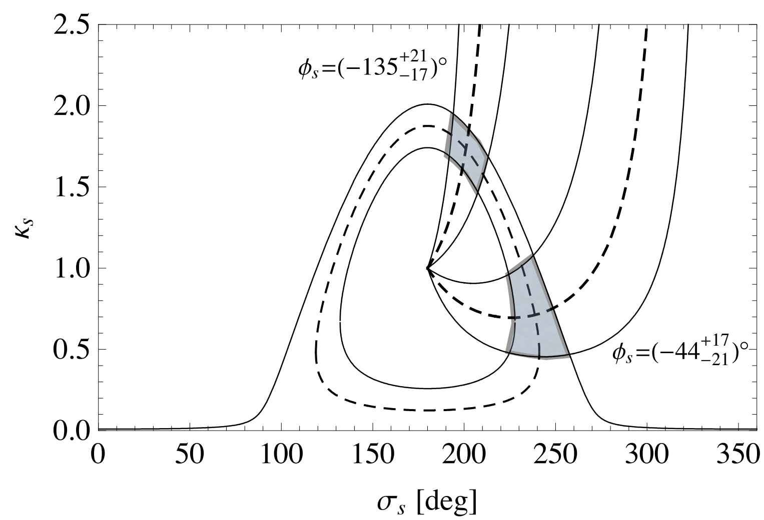
- CP-violating NP effects, i.e. $\phi_s^{\rm NP} \neq 0^\circ$, would be indicated as follows:

  – The *untagged* observables depend on *two* exponentials;

  – *sizeable* values of the CP-violating asymmetries.

Interesting Results from the Tevatron

- First *tagged* analyses of $B_s \to J/\psi\phi$ by CDF and DØ:
  - T. Aaltonen *et al.* (CDF Collaboration), arXiv:0712.2397 [hep-ex]
  - V.M. Abazov *et al.* (DØ Collaboration), arXiv:0802.2255 [hep-ex]
- UTfit Collaboration: arXiv:0803.0659 [hep-ph]
  - Performing an average of CDF and DØ and taking other constraints into account, it is speculated about CP-violating NP in B_s^0–$\bar{B}_s^0$ mixing.
- Heavy Flavour Averaging Group (HFAG): $\phi_s^{\rm NP} = \left(-44^{+17}_{-21}\right)^\circ \vee \left(-135^{+21}_{-17}\right)^\circ$



[Update of P. Ball & R.F. (2006)]

$\Rightarrow$!? Fortunately, ϕ_s is very accessible @ LHCb ...

Prospects for ϕ_s Measurements at the LHC

- Experimental reach @ LHCb: *very impressive ...*
  - One nominal year of operation, i.e. 2 fb^{-1}: $\sigma(\phi_s)_{\rm exp} \sim 1^\circ$
  - LHCb upgrade with integrated lumi of 100 fb^{-1}: $\sigma(\phi_s)_{\rm exp} \sim 0.2^\circ$

- However: *have to include hadronic SM corrections to match this ...*
  - Penguin shift $\Delta\phi_s$ could induce CP asymmetries as large as $\sim -10\%$, while $\sin\phi_s^{\rm SM} \approx -3\%$ (supported by $B^0 \to J/\psi\pi^0$ data analysis).
  - Control channel: $\boxed{B_s^0 \to J/\psi[\to \ell^+\ell^-]\bar{K}^{*0}[\to \pi^+K^-]}$
    - ∗ Search for this decay at the Tevatron: $\Rightarrow$ first constraints on $\Delta\phi_s$.
    - ∗ Fully pin down $\Delta\phi_s$ at LHCb (perform corresponding studies).
    - ∗ Offers also internal checks of the $SU(3)$ flavour symmetry :-)

[S. Faller, R.F. & T. Mannel (2008) $\rightarrow$]

Closer Look @ SM Penguin Effects

- CP asymmetries:

$$\frac{|A_f(t)|^2 - |\overline{A}_f(t)|^2}{|A_f(t)|^2 + |\overline{A}_f(t)|^2} = \frac{\hat{A}_{\rm D}^f \cos(\Delta M_s t) + \hat{A}_{\rm M}^f \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}_{\Delta\Gamma}^f \sinh(\Delta\Gamma_s t/2)}$$

- Impact of hadronic effects:

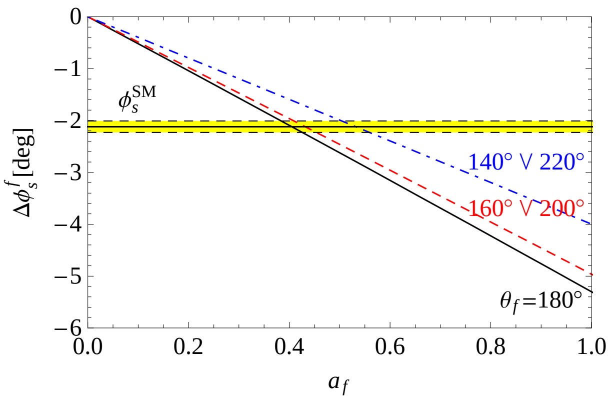
$$\boxed{\eta_f \hat{A}_{\rm M}^f / \sqrt{1 - (\hat{A}_{\rm D}^f)^2} = \sin(\phi_s + \Delta\phi_s^f)}$$

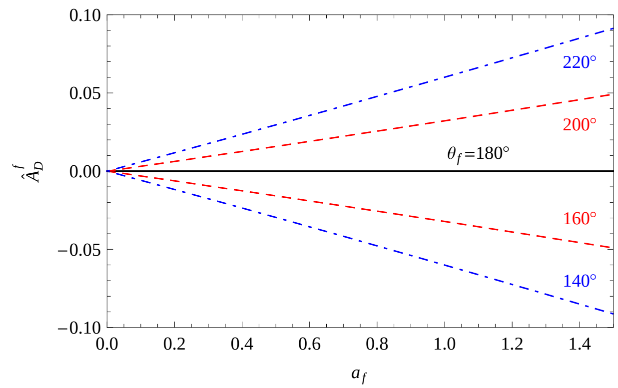
$$\sin\Delta\phi_s^f = \frac{2\epsilon a_f \cos\theta_f \sin\gamma + \epsilon^2 a_f^2 \sin 2\gamma}{N_f \sqrt{1 - (\hat{A}_{\rm D}^f)^2}}$$

$$\cos\Delta\phi_s^f = \frac{1 + 2\epsilon a_f \cos\theta_f \cos\gamma + \epsilon^2 a_f^2 \cos 2\gamma}{N_f \sqrt{1 - (\hat{A}_{\rm D}^f)^2}},$$

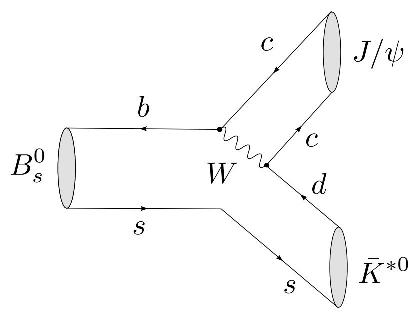
$$N_f \equiv 1 + 2\epsilon a_f \cos\theta_f \cos\gamma + \epsilon^2 a_f^2$$

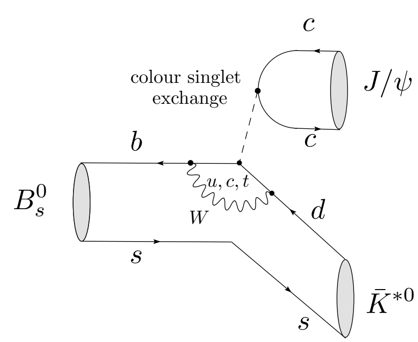
- <u>Illustration of the effects:</u>

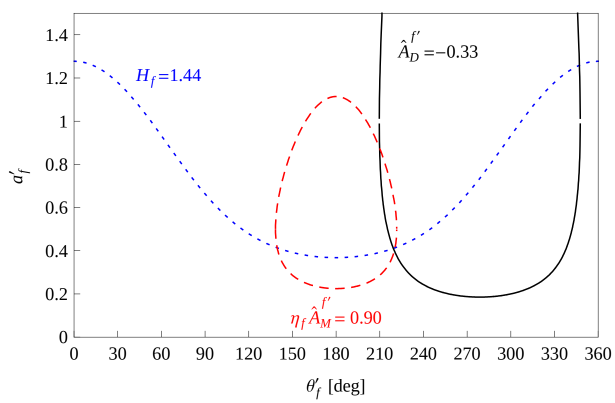


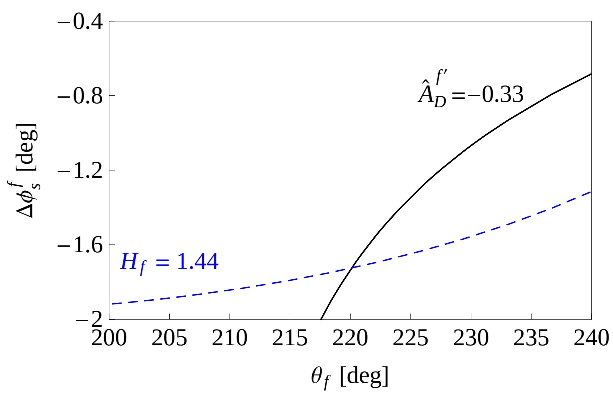


- <u>Control of the effects through $B_s^0 \to J/\psi \bar{K}^{*0}$:</u>





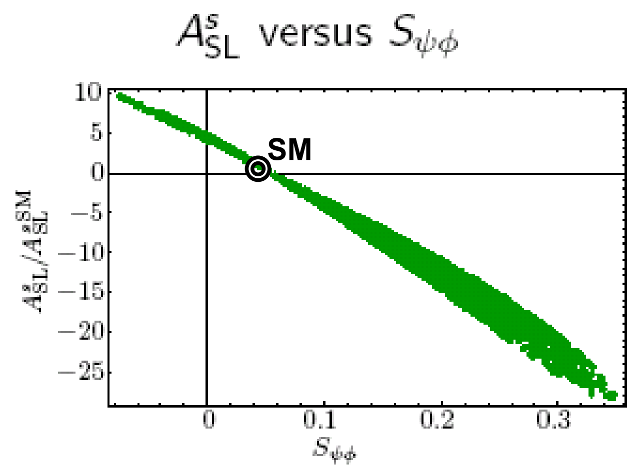




[S. Faller, R.F. & T. Mannel (2008)]

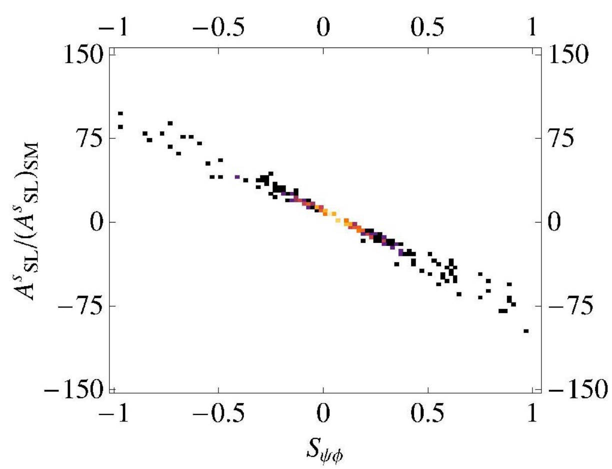
Examples of Specific BSM Analyses

- Littlest Higgs Model with T-Parity (LHT):[3] [⟶ talk by Goto]



[Blanke, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig & Weiler]

- Warped Extra Dimensions: [⟶ talks by Weiler & Gori]



[Blanke, Buras, Duling, Gori & Weiler (2008)]

[3] $A^{s\,SM}_{SL} \sim 2 \times 10^{-5}$: "wrong-charge" lepton asymmetry measuring CP violation in B^0_s–$\bar{B}^0_s$ oscillations.

Further Benchmark Decays

for the

LHCb Experiment

$\longrightarrow$ very rich physics programme ...

[For experimental overview, see talk by Tatsuya Nakada]

Two Major Lines of Research

1. Precision measurements of γ:

- Tree strategies, with expected sensitivities after 1 year of taking data:
  - $B_s^0 \to D_s^{\mp} K^{\pm}$: $\sigma_\gamma \sim 14^\circ$
  - $B_d^0 \to D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the
  - $B^{\pm} \to D^0 K^{\pm}$: $\sigma_\gamma \sim 5^\circ$

  current B-factory data: $$\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (70^{+27}_{-30})^\circ & \text{[CKMfitter]} \\ (78 \pm 12)^\circ & \text{[UTfit]} \end{cases}$$

- Decays with penguin contributions:
  - $B_s^0 \to K^+ K^-$ and $B_d^0 \to \pi^+\pi^-$: $\sigma_\gamma \sim 5^\circ$
  - $B_s^0 \to D_s^+ D_s^-$ and $B_d^0 \to D_d^+ D_d^-$

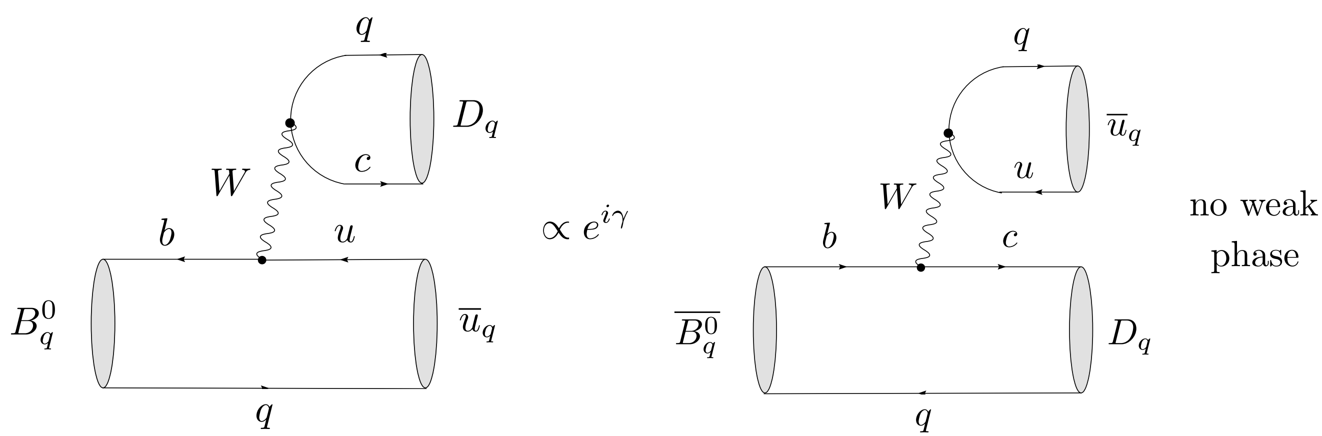
2. Analyses of rare decays: [see discussion above & talks by Ball & Hiller]

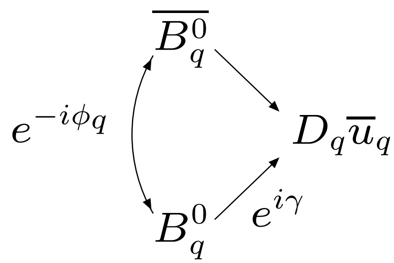
- $B_s^0 \to \phi\phi$
- $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \mu^+\mu^-$ (ATLAS & CMS are competitive!)
- $B_d^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$; ...

$\to$ let's have a closer look at some decays ...

CP Violation in $B_s \to D_s^{\pm} K^{\mp}$ and $B_d \to D^{\pm}\pi^{\mp}$

- General case:





$\boxed{\phi_q + \gamma}$

- $\underline{q = s}$: $D_s \in \{D_s^+, D_s^{*+}, ...\}$, $u_s \in \{K^+, K^{*+}, ...\}$:

  $\longrightarrow$ hadronic parameter $X_s e^{i\delta_s} \propto R_b \Rightarrow$ *large* interference effects!

- $\underline{q = d}$: $D_d \in \{D^+, D^{*+}, ...\}$, $u_d \in \{\pi^+, \rho^+, ...\}$:

  $\longrightarrow$ hadronic parameter $X_d e^{i\delta_d} \propto -\lambda^2 R_b \Rightarrow$ *tiny* interference effects!

- $\cos(\Delta M_q t)$ and $\sin(\Delta M_q t)$ terms of the time-dependent decay rates:

$$\Rightarrow \boxed{\text{theoretically } \textit{clean} \text{ determination of } \phi_q+\gamma} \quad \xrightarrow{\phi_q \text{ known}} \quad \boxed{\gamma}$$

[Dunietz & Sachs (1988); Aleksan, Dunietz & Kayser (1992); Dunietz (1998); ...]

- However, there are also problems:
  - We encounter an *eightfold* discrete ambiguity for $\phi_q+\gamma$!?
  - In the $q=d$ case, an additional input is required to extract X_d since $\mathcal{O}(X_d^2)$ interference effects would have to be resolved $\rightarrow$ *impossilbe* ...

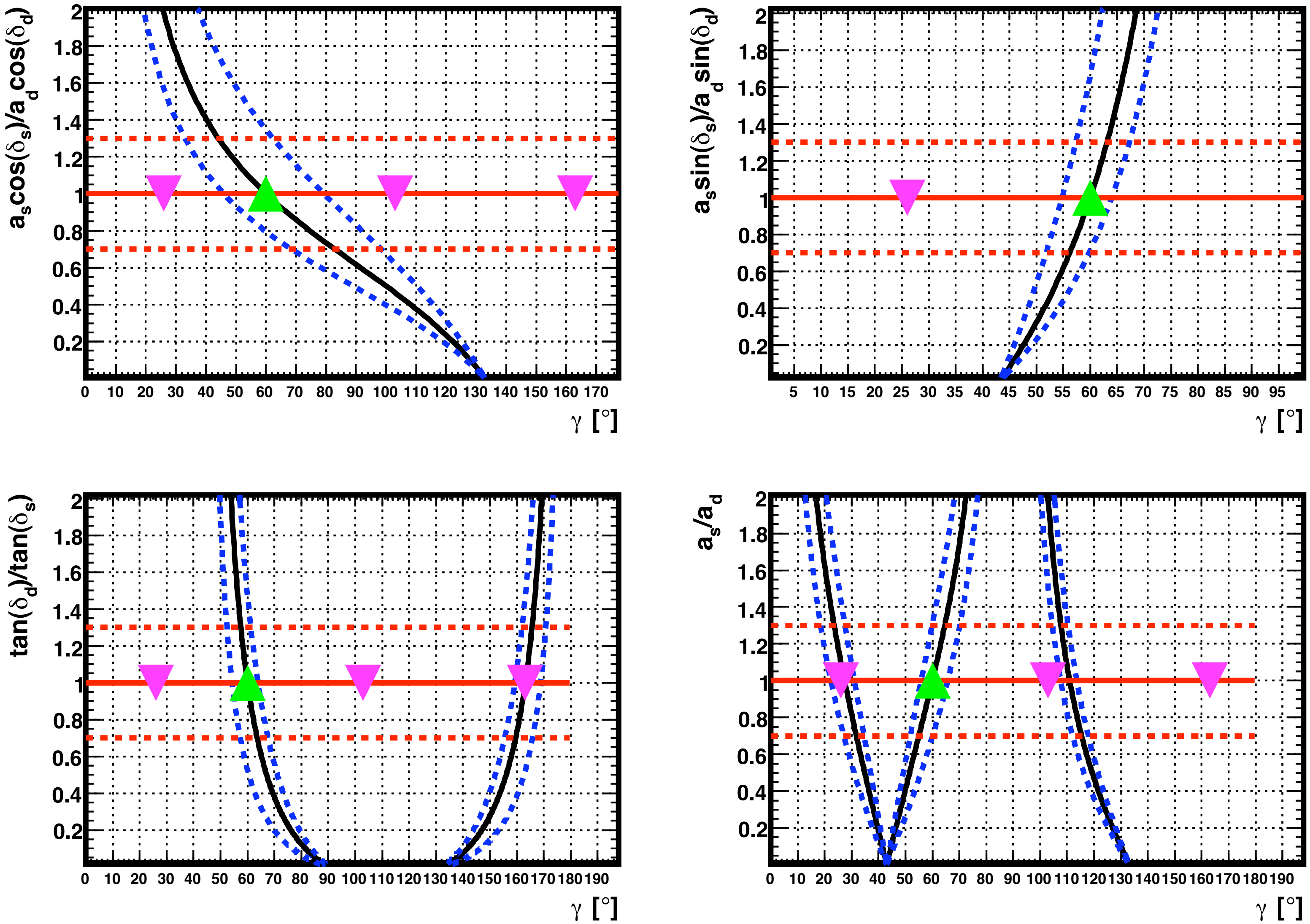
- Combined analysis of $B_s^0 \to D_s^{(*)+}K^-$ and $B_d^0 \to D^{(*)+}\pi^-$: [R.F. (2003)]

$$\boxed{s \leftrightarrow d} \quad \Rightarrow \quad U\text{-spin symmetry provides an interesting playground:}$$ [4]

  - An *unambiguous* value of γ can be extracted from the observables!
  - To this end, X_d has *not* to be fixed, and X_s may *only* enter through a $1+X_s^2$ correction, which is determined through *untagged* B_s rates!
  - Promising studies by LHCb: $\boxed{\longrightarrow}$

[4] The U-spin is an $SU(2)$ subgroup of the $SU(3)_{\rm F}$ flavour-symmetry group, connecting d and s quarks in analogy to the conventional isospin symmetry, which relates d and u quarks to each other.

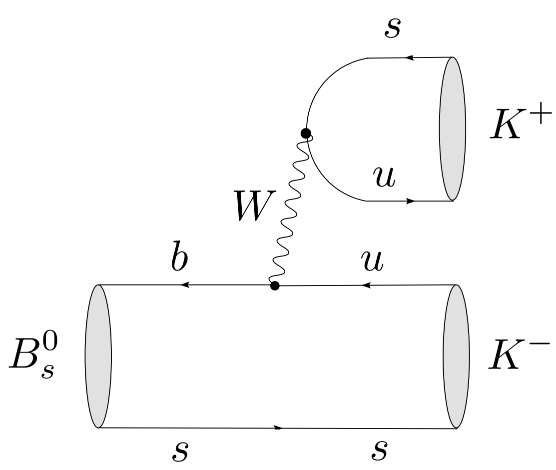
EXAMPLE RESULT: γ=60°, δ=60° (5 YEARS)

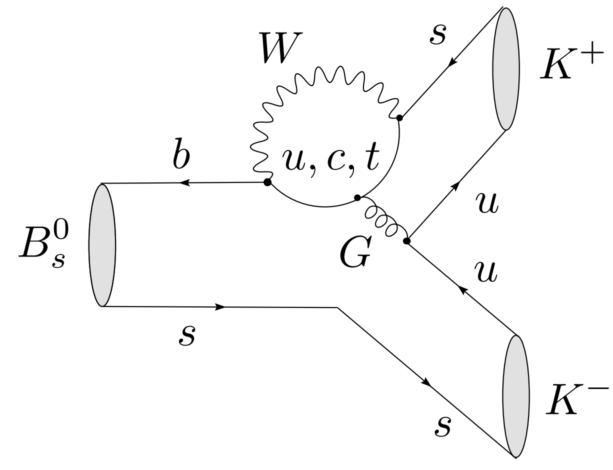


[V. Gligorov @ CERN TH Flavour Institute, June 2008]

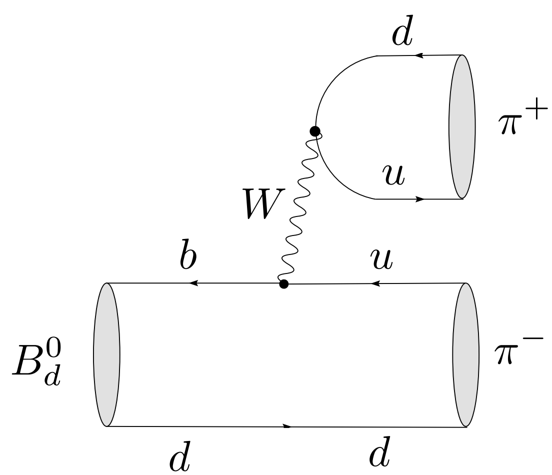
The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

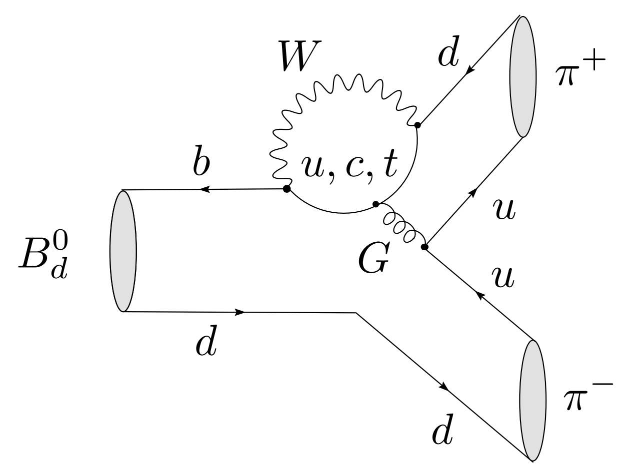
- $B_s^0 \to K^+K^-$:





- $B_d^0 \to \pi^+\pi^-$:





$\Rightarrow$ $\boxed{s \leftrightarrow d}$

- Structure of the decay amplitudes in the Standard Model:

$$A(B_d^0 \to \pi^+\pi^-) \quad \propto \quad \left[e^{i\gamma} - de^{i\theta}\right]$$

$$A(B_s^0 \to K^+K^-) \quad \propto \quad \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2}\right) d' e^{i\theta'}\right]$$

$$\boxed{d\, e^{i\theta} = \frac{\text{“penguin”}}{\text{“tree”}}\bigg|_{B_d\to\pi^+\pi^-}, \quad d'\, e^{i\theta'} = \frac{\text{“penguin”}}{\text{“tree”}}\bigg|_{B_s\to K^+K^-}}$$

[d, d': real hadronic parameters; θ, θ': strong phases]

- General form of the CP asymmetries:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = G_1(d, \theta, \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = G_2(d, \theta, \gamma, \phi_d)$$

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) = G_1'(d', \theta', \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = G_2'(d', \theta', \gamma, \phi_s)$$

- $\phi_d = 2\beta$ (from $B_d \to J/\psi K_{\rm S}$) and $\phi_s \approx 0$ are known parameters:

  – $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ & $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$: $\Rightarrow$ $\boxed{d = d(\gamma)}$ (clean!)

  – $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$ & $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$: $\Rightarrow$ $\boxed{d' = d'(\gamma)}$ (clean!)

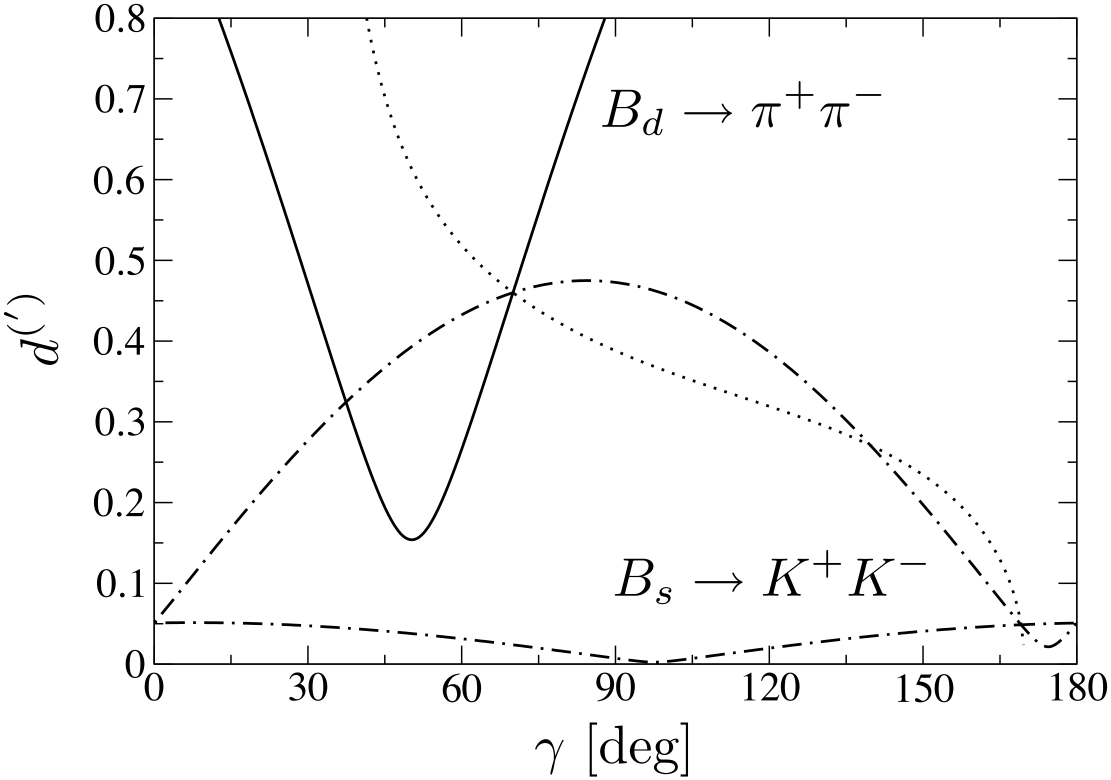
- Example (inspired by the current data):

  - Input parameter:

    * $\phi_d = 42.4°$, $\phi_s = -2°$, $\gamma = 70°$, $d = d' = 0.46$, $\theta = \theta' = 155°$

  - CP asymmetries:

    * $B_d \to \pi^+\pi^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = -0.24$, $\mathcal{A}_{\rm CP}^{\rm mix} = +0.59$
    * $B_s \to K^+K^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = +0.09$, $\mathcal{A}_{\rm CP}^{\rm mix} = -0.23$



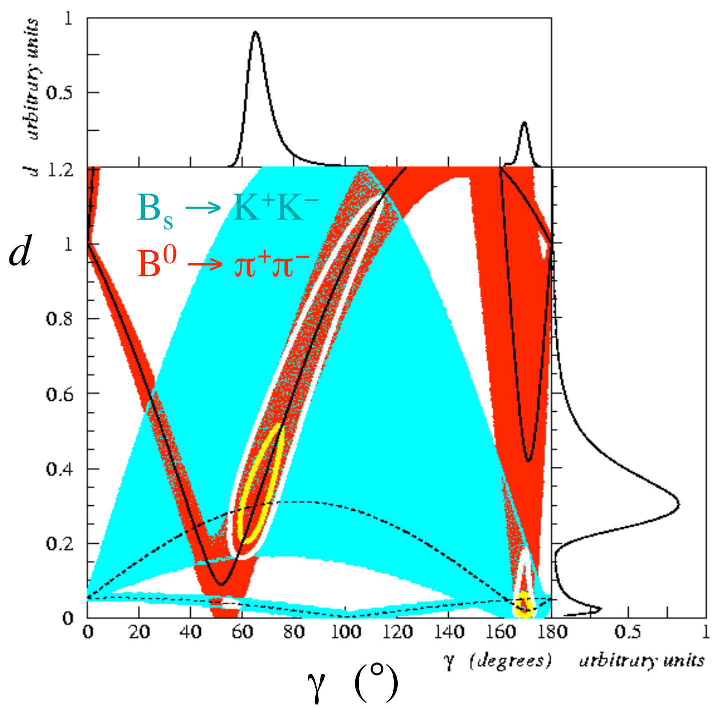
- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

U-spin symmetry $\Rightarrow$

  - Determination of γ and hadronic parameters $d(=d')$, θ and θ'.
  - Internal consistency check of the U-spin symmetry: $\theta \stackrel{?}{=} \theta'$.

[R.F. (1999); current picture: $\gamma = (66.6^{+4.3+4.0}_{-5.0-3.0})^\circ$ arXiv:0705.1121 [hep-ph]]

- Detailed studies show that this strategy is very promising for LHCb:



$\to$ experimental accuracy for γ of a few degrees!

[CERN-LHCb/2003-123 & 124; recent study: A. Carbone @ CERN TH Flavour Institute]

Targets for an e^+e^- "Super-Flavour Factory":

→ aim @ luminosity $\sim 10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

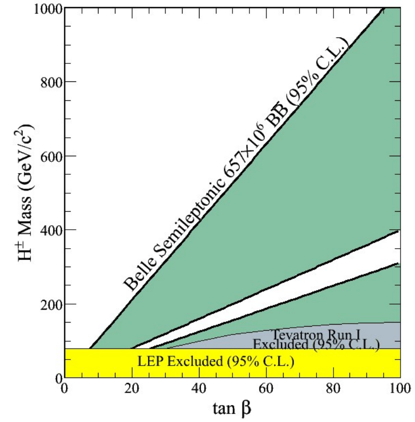
- Super$B$: proposal with new site close to Rome;
  [http://www.pi.infn.it/SuperB/]

  [→ talk by T. Nakada]

- SuperKEKB: KEK/Japan
  [http://superb.kek.jp/]

→ physics "left" by LHCb ($\oplus$ possible upgrade)?

Rare Decays @ Super-Flavour Factory



1. Semileptonic tree processes (tiny BRs):[5]
   - BR$(B \to \tau\nu)$: $\sim (3$–$4)\%$
   - BR$(B \to D\tau\nu)$: $\sim (2$–$3)\%$

     $\to$ constraints on non-SM charged Higgs:

2. Loop processes: $\to$ **powerful NP probes**
   - Mixing-induced CP asymmetry $S(B^0 \to \rho^0\gamma)$: ~ 0.08–0.12
   - Mixing-induced CP asymmetry $S(B^0 \to K_{\rm S}\pi^0\gamma)$: ~ 0.02–0.03
   - CP asymmetry $A_{\rm CP}(b \to s\gamma)$: ~ 0.004–0.005
   - Forward–backward asymmetry $A_{\rm FB}(B \to X_s\ell^+\ell^-)$: $\hat{s}_0 \sim (4$–$6)\%$
   - Branching ratio BR$(B \to K\nu\bar{\nu})$: $\sim (16$–$20)\%$
   - Branching ratio BR$(B \to X_s\nu\bar{\nu})$ ("cleanest" rare B decay process!).

3. Lepton Flavour Violation: $\to$ **measureable in various NP scenarios**
   - BR$(\tau \to \mu\gamma)$: $\sim (2$–$8) \times 10^{-9}$
   - BR$(\tau \to \mu\mu\mu)$: $\sim (0.2$–$1) \times 10^{-9}$
   - BR$(\tau \to \mu\eta)$: $\sim (0.4$–$4) \times 10^{-9}$

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[5] Experimental sensitivities refer to $(50$–$75)$ ab^{-1} [Browder *et al.*, arXiv:0710.3799 [hep-ph]].

Hadronic B Decays @ Super-Flavour Factory

1. Control of the SM corrections to "golden" decays: $\longrightarrow \phi_q$
   - $B_d^0 \to J/\psi \pi^0$ to control the penguin effects in $B_d^0 \to J/\psi K_{\mathrm{S,L}}$.
   - Also $B_d^0 \to J/\psi \rho^0$ would be interesting for $B_s^0 \to J/\psi \phi$.
2. Search for NP in hadronic $b \to s$ penguin processes:
   - CP violation in $B_d^0 \to \pi^0 K_{\mathrm{S}}$ offers most interesting observables.
   - Requires also measurements of other $B \to \pi^0 K$ and $B \to \pi^0 \pi$ decay observables as input for the theoretical analysis.
3. Pure tree decays:
   - $B_d \to D_{\pm} K_{\mathrm{S(L)}}$ (and $B_s \to D_{\pm} \eta^{(\prime)}$, $B_s \to D_{\pm} \phi$):

     $\longrightarrow$ unambiuous clean determinations of γ
   - $B_d \to D_{\pm} \pi^0, D_{\pm} \rho^0, \ldots$ (and $B_s \to D_{\pm} K_{\mathrm{S(L)}}$):

     $\longrightarrow$ extremely clean determinations of $\sin \phi_q$ ($\longrightarrow$ compare with 1.)

Concluding Remarks

Where do we stand in B physics?

- Tremendous progress in B physics during the recent years:

  Fruitful interplay between theory and experiment

  - e^+e^- B factories: have produced $\sum \mathcal{O}(10^9)$ $B\bar{B}$ pairs;
  - Tevatron: has recently reported exciting B_s results.

- Status in Spring 2009:
  - The data agree globally with the Kobayashi–Maskawa picture!
  - But we have also hints for discrepancies: $\to$ first signals of NP?

- New perspectives for B-decay studies @ LHC (restart in September '09):
  - Large statistics and full exploitation of the B_s physics potential, thereby complementing the physics programme of the e^+e^- B factories.
  - Precision determinations of γ: $\to$ key ingredients for NP searches!
  - Powerful studies of rare decays: $B_s^0 \to \phi\phi$, $B_{s,d}^0 \to \mu^+\mu^-$, ...

An Optimistic Scenario: Let's Hope Nature is Kind!

- First unambiguous signals for NP @ LHC in the flavour sector:
  - Could show up @ LHCb in the CP asymmetries of $B_s^0 \to J/\psi\phi$.
  - Would immediately imply *new sources of CP violation!*
  - Could go hand in hand with new CP-violating effects in the $b \to s$ penguin decay $B_s^0 \to \phi\phi$ (as well as in $B^0 \to \phi K_S$, $B^0 \to \pi^0 K_S$).
  - Study correlations with rare decays: $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to K^{*0}\mu^+\mu^-$, ...

NP reach limited by precision!

- Ideally, NP signals would be complemented by high-Q^2 collider physics:
  - Direct signals of new particles @ ATLAS and CMS!
  - Measure masses, couplings of new particles (e.g. Z' boson, SUSY).
  - Flavour-physics observables determine then new flavour- and CP-violating structures (NP particle masses, couplings important input).

NP reach limited by the energy of the LHC (or ILC, CLIC, ...)!

Next Decade: Most Exciting for Particle Physics!

- Expect to find Higgs(es) or an alternative for EW symmetry breaking!
- Hope to find also evidence for physics beyond the SM @ LHC:

1. Establish NP signals unambiguously, i.e. distinguish from SM effects.
2. Study the properties of NP and find out what it is (SUSY, extra dimensions, little Higgs models, Z' models, 4th generation, ... ?).

B (flavour) physics is an integral part of this adventure!

- Get back to the long-standing "big" questions:

– Dark matter of the Universe.
– Baryon asymmetry of the Universe ...

- Decide on new experimental programmes and get them started:

LHC upgrade options (luminosity vs. energy), LHCb detector upgrade, e^+e^- super-B factories (SuperKEKB, Super$B$), $K \to \pi\nu\bar{\nu}$ experiments (CERN, J-PARC), ILC, CLIC, ... are already under discussion.

- The interplay between theory and experiment should allow us to make significant progress towards the formulation of a "new" Standard Model:

$\longrightarrow$ may revolutionize our picture of the Universe!